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POSITION PAPER ON TURBULENT FLOW SEPARATION

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1. INTRODUCTION

Substantial advances in computational fluid dynamics (CFD) have been made over the past several years. The obvious stimulus for this growth has been the recognition of the potential for solving aerodynamic problems of interest with larger, faster computers. A primary focus of the effort with regard to NASA's Aerodynamic program is the eventual use of CFD to develop new efficient aircraft in a complementary fashion with large wind tunnels so that timely, less costly designs can be achieved. Before that eventually arises, computational fluid dynamics must succeed in simulating flows over real aircraft shapes or their components, including the difficult cases where viscous, turbulent flows are present.

The status of computational aerodynamics is briefly summarized in Table 1. The stage of approximation of the governing equations has been divided into four progressively more complex formulations, culminating with the viscous time-dependent Navier-Stokes equations. The rapid development, particularly since the start of this decade is quite evident and is directly attributable to the availability of larger computers and the accompanying progress in numerical techniques. Presently the development of nonlinear inviscid methods is nearing completion. Much of the present work focuses on computational efficiency. A serious limitation of inviscid techniques is that they cannot account for flow separation which is important in predicting aircraft design performance. In order to account for those situations, solutions to the Navier-Stokes equations, or their approximations, are required. Techniques for accomplishing this using their Reynolds-averaged form are in the early stages of development. However, the accuracy of turbulence modeling now largely limits the success of these computations and one important item leading to successful computations is turbulence modeling.

Beyond this stage of approximation is the development of techniques employing the complete, time-dependent Navier-Stokes equations. Already remarkable achievements have been illustrated for very simple problems, but it will be well into the next decade before any complex aerodynamic flows can be addressed.

Since the successful near term development of computational aerodynamics depends, to a great extent, on turbulence modeling, a concerted effort is now underway to develop sufficiently accurate turbulence models in a time-frame consistent with the development of computational aerodynamics. Because turbulence modeling is empirical by nature, successful development relies on a substantial data base, not only for verification of postulated models, but for providing guidance in model development.

Within NASA, the turbulence modeling for computational aerodynamics is being approached in several ways, each relying on key experimental input. For the near term, computer limitations force solutions to realistic aerodynamic problems through implementation of modeling consistent with the application of the time-averaged Navier-Stokes equations, or appropriate approximations of them. For the long term, application of modeling concepts consistent with the use of the complete, time-dependent Navier-Stokes equations are being studied.

While the spectrum of problems under study within NASA is purposely broad, this position paper will focus on just one class- those where separation is induced by the presence of a shock wave or some other geometrical constraint such as a deflected surface and where that separation has a significant influence on the outer inviscid flow that develops. Also, it will focus on two dimensional flows, but an example of a three dimensional flow will be presented because the results may indicate that some 3-dimensional, separated flows may be predicted with better confidence than two-dimensional ones, even though primitive turbulence models are employed.

A reference list that includes work on the broader spectrum of our turbulence modeling studies is included for completeness.

2. SCOPE

Compressible viscous flows with separation induced by or influenced by viscous-inviscid interactions are described by the Navier-Stokes equations. These equations are necessary to describe both the elliptic nature of separated flow fields and the complex coupling between the viscous and inviscid regions of the flow where interactions are strong, such as shock impingements on boundary layers or asymmetric near wakes. At Reynolds numbers associated with aircraft flight conditions the viscous flow regions are predominantly turbulent. While the Navier-Stokes equations themselves adequately describe such flows, numerical solutions of engineering accuracy can be realized, at present, only when Reynolds averaging is used to eliminate the small time and length scales inherent in turbulent flows. The resulting Reynolds stresses must then in turn be described by empirically modeled equations. Modeling approaches consistent with the use of the Reynolds-averaged Navier-Stokes equations have been progressing in a straightforward manner. The objective is to introduce successively more complex models that include successively more plausible physics into various codes that solve the Navier-Stokes equations until a reasonably accurate predictive method is resolved. This process is progressing from algebraic eddy viscosity models, through multi-equation eddy viscosity models, and finally on to models developed from the complete Reynolds stress equations. Predictability is assessed at all levels and the process can be discontinued if success is demonstrated. Model verification and guidance are provided by comparisons of computed results with an ever increasing data base being developed by performing "building block experiments."

Numerical schemes have been developed that can solve the system of Navier-Stokes and turbulence model equations with reasonable efficiency. The schemes are both implicit and mixed implicit/explicit and are described fully elsewhere.[22,23,31] Computational grids are constructed that support only the features of physical importance or interest. In this sense, solutions to the complete Navier-Stokes equations are not actually realized but rather to a suitable subset that still retains the elliptic nature of the flow and describes the viscous-inviscid interaction. Generally this results in the details just at the points of separation or reattachment not being resolved, but rather the general location of such points (to the resolving ability of the computational mesh) and their influence on the remaining flow field. This has been found to provide for adequate engineering computations and contributes greatly to the computational efficiency.

"Building block" experiments that support the development of the computations are also being carried out both within NASA and at several participating universities. Descriptions of the "building block" concept for 2-dimensional flows are given in refs. 17 and 26. These carefully controlled experiments are designed to give turbulence modeling information and to provide computational verification over practical ranges of Mach and Reynolds numbers. Complimentary computations are carried out for the precise geometry of the experiments and employ boundary conditions consistent with the experimental ones.

3. STATUS OF THE PROBLEM

The status of the studies is illustrated by some examples of comparisons of computation and experiment taken from recent publications.

Supersonic flows. - The separation of a supersonic turbulent boundary layer undergoing separation due to the impingement of a shock wave or deflection of a control surface is one class of problems under study. The geometry of typical building block experiments used in developing successful numerical simulations for two-dimensional flows is shown in figures 1 and 2. In both examples, a shock wave of sufficient strength is developed and it causes the oncoming turbulent boundary layer to separate. Computations for these flows with codes that solve the time-dependent form of the Reynolds-averaged Navier-Stokes equations employing various eddy viscosity formulations to model the turbulence have been reported.[8] Each of the models employs constants developed for incompressible flows and attempts were made to alter them. Examples of the results are compared with experiment in figures 3 and 4. Examples for other shock strengths are given in ref. 8 along with an overall assessment of the results when all the cases are considered.

An important consideration to the design of control surfaces or engine inlets where shocks may develop is the overall pressure rise through the interaction. For all computations of supersonic shock-boundary layer interactions reported thus far, the overall pressure rise is always predicted with good accuracy. However, in order to assess the development of numerical simulation s involving separation which is our purpose here, it is well to consider the significant zones of the interaction: the zone of upstream influence caused by the presence of the separation bubble, the zone of separation itself, and finally the zone in and downstream of reattachment.

As illustrated in figures 3 and 4, the solutions with the simple 0-equation turbulence model (algebraic eddy viscosity) fail to predict the proper upstream influence, the presence of a plateau in the pressure distribution and the skin friction. The higher-order models which solve additional differential equations for turbulent kinetic energy and dissipation are significantly better at predicting the upstream influence and presence of a plateau in the pressure over the separation bubble. Even in the separated region, they seem to predict the skin friction reasonably well. However, downstream of reattachment, while they predict the proper overall pressure rise, they fail to consistently predict the proper skin friction although they are always better than the 0-equation results. Comparisons of velocity and turbulence kinetic energy profiles are given in ref. 8. In the separated zone and downstream of reattachment the predictions using the higher order models show better qualitative agreement with the experimental profile data than the zero order model predictions, but quantitative agreement is not always found. The trends of separation extent with Reynolds number are also predicted correctly by all of the models. An example is shown in figure 5.

While the details of the flow in the separated region and downstream near the reattachment region are not predicted consistently for all the 2-dimensional building block experiments, it is of interest to note that 3-dimensional flows with shock induced separations apparently are easier to compute. The geometry of such flows is shown in figure 6. A swept shock wave is developed that impinges and interacts with the oncoming turbulent boundary layer causing the flow to "separate" in a 3-dimensional sense. Results of comparisons between experiment and computations using a simple 0-equation eddy viscosity shows excellent agreement with mean surface quantities, axial and cross-flow velocity profiles, and flow direction-angles profiles.[3] Examples are given in figures 7 and 8. Evidently, when the separated region does not have a confined region of reversed flow, the prediction using a simple eddy viscosity model is very satisfactory.

Transonic flows. - Transonic flows developed over airfoils, fuselages and wings are of considerable interest to aerodynamicists. Shock waves can occur and large regions of separation develop. The effects of Mach and Reynolds numbers must be understood as scaling of experimental findings to flight conditions is necessary. Some examples that illustrate the status of progress toward simulating these flows are given below.

A test flow used to develop information on the turbulent boundary layer in the presence of a shock wave for Mach number and Reynolds number ranges of interest is shown in figure 9. A shock wave is developed in a circular test section by use of a downstream shock generator. The resulting flow is axisymmetric. Mean and turbulence data have been obtained and computations using the time dependent-Reynolds averaged equations with various eddy viscosity models have been made.[8] The comparison of computation and experiment for surface skin friction and pressures is shown in figure 10. With the exception of the computation using the Jones-Launder model, the higher-order models predict the experimental pressures and skin friction quite adequately. The exception is due in part to numerical difficulties. The predictions of Reynolds number effects are also very satisfactory when the higher order models are employed. See figure 11. While these results are very encouraging, it must be pointed out that the zone of separation is rather small and its effect on the development of the outer inviscid flow is less important than the thickening of the boundary layer in the vicinity of the shock-wave and downstream of it.

A flow where large regions of shock-induced separation develop is under study. The geometry of the experimental arrangement is shown in figure 12. A circular arc airfoil spans the test section of a high Reynolds number blow-down wind tunnel. The upper and lower walls are contoured to prevent shock waves developing at the outer boundary. Both mean and fluctuating measurements for the region downstream of the shock wave that develops have been obtained.[5] Figure 13 shows a shadowgraph of the flow field and the velocity profiles obtained with a laser velocimeter. The flow is separated from a shock wave to a point beyond the trailing edge. Figure 14 shows the profiles of velocity, turbulent shear stress and turbulent kinetic energy. The shear layer that develops downstream of the shock wave is similar to that developed behind a rearward facing step. Computations of this flow have also been made using a zero-equation turbulence model.[5] The shock wave shape is compared with the computed Mach contours in figure 15 and the surface pressures and skin friction are compared in figure 16. In the computations, the shock wave does not have proper obliqueness and hence predicts pressures that are significantly higher downstream, although the separation extent is predicted quite well. More work remains to be done on the modeling of this flow.

It also can be pointed out that the airfoil experiment developed an unsteady flow with alternating shock induced and trailing-edge separation at at lower Mach numbers. Mean and turbulence data have been obtained.[1] Computations using the zero-equation steady flow model also predict the unsteady flow but the reduced frequency is lower by about twenty percent and the fluctuating surface pressures are somewhat higher.[1,5] The important implication of this result is that it may be possible to predict airfoil buffett boundaries with the advanced computer codes now under development. This new avenue of research is under study at the present time.

4. FUTURE REQUIREMENTS

The preceding examples have been used to illustrate the status of our ability to model one class of separated flows. Computations employing the time-dependent Reynolds averaged Navier-Stokes equations have been able to simulate all of the relevent flow features, even for unsteady, coupled shock-induced-trailing edge separations. Considering the broad spectrum of flow conditions and geometries that have been studied, the results are viewed optimistically. Clearly, however, our ability to model the turbulence in the separated regions of the flow and downstream needs to be improved before we can compute flows with engineering confidence. By no means have we exhausted all the possibilities available to us to improve on turbulence models. Viewed in this perspective, and considering that the ultimate objective is to predict 3-dimensional flows, much work remains before us.

Some major areas of concern seem critical to the development of adequate turbulence models. For example: the roll of unsteadiness and/or pressure gradient on the development of the separating shear layer and its reattachment on surfaces or its effect on the development of the near-wake regions behind airfoils;

the importance, if any, of the presence of a wall on the development of a large separated region; and the importance of the presence of large and small turbulent scales on the development of shear layers and separated regions. Added to these are the areas of concern regarding the numerical simulation of these complex flows. For example, the determination of adequate grids that can support development of shock waves, especially near their foot where experiments show significant obliqueness and computations do not; shock fitting versus shock capture techniques; and near wake grid development that satisfies the physics of the flow with regard to mixing and pressure gradient effects.

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TABLE I. - STATUS OF COMPUTATIONAL AERODYNAMICS

Stage of approximation for equations	Readiness time period 2D airfoil / 3D wing / 3D wing-body	Limitations	Pacing Item
Inviscid Linearized	1930's 1950's 1960's Used in current aircraft design	Slender configurations Small angle of attack Perfect gas No transonic flow No hypersonic flow No flow separation	
Inviscid nonlinear	1971 1973 1977 Development nearing completion	No flow separation	Code development
Viscous time-dependent, Reynolds-averaged	1975 1979 1982 Early stage of development	Accuracy of turbulence model Computer capacity, speed	Turbulence modeling Development of advanced computer
Viscous time dependent	Mid 1980's	Accuracy of sub-grid turbulence model Computer capacity, speed	Development of advanced computer